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HIGHWAY RESEARCH REPORT

EXPERIMENTAL CATHODIC PROTECTION OF A BRIDGE DECK

INTERIM REPORT

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STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF TRANSPORTATION

DIVISION OF HIGHWAYS

TRANSPORTATION LABORATORY

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16. ABSTRACT

An electrically conductive asphalt concrete was made by substituting coke breeze for the natural aggregate. By paving a bridge deck with the electrically conductive asphalt concrete, it was found that cathodic protection could be applied to the reinforcing steel.

The cathodic protection was measured to be effective when corrosion of steel strips imbedded in concrete containing 10% calcium chloride by weight of the cement was stopped.

It is estimated that for the approximately 330 square feet (307.6 sq.m.) of bridge deck under cathodic protection, the top mat of reinforcing steel has an applied current density of 0.7 milliamperes (MA) per square foot (7.5 ma/sq.m.) of steel surface. The total current used is about 1.0 ampere with a driving voltage of 1.65 volts for a total power requirement of 1.65 watts.

As an experimental method of repair, two polymers and an epoxy were injected to bond the undersurface fractures. It was observed that the epoxy could be injected to effect a repair only under certain conditions. In all cases where the concrete emitted a hollow sound

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RONALD REAGAN, Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
TRANSPORTATION LABORATORY
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January 1974

Trans. Lab. No. 635117-4
FHWA No. D-3-12

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a interim research report titled:

EXPERIMENTAL CATHODIC PROTECTION OF A

BRIDGE DECK

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Very truly yours,

JOHN L. BEATON
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Attachment

Abstract (Continued)

when struck with a hammer, the epoxy could be injected. However, in many cases, epoxy could not be injected when the concrete emitted a hollow sound from only the use of the chain drag, but not when the hammer was used.

It is estimated that the cost of the cathodic protection installation was about $3.00 per square foot of deck ($32/sq.m.).

REFERENCE: Stratfull, R. F., "Experimental Cathodic Protection of a Bridge Deck", State of California, Department of Transportation, Transportation Laboratory, Research Report No. 635117-4, FHWA D-3-12, January 1974

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The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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INTRODUCTION

A number of reports in the literature have related to the problem of bridge deck deterioration to the use of deicing salts[1-12]. In general, the reports have been concerned with detection and determination of causes of reinforcing steel corrosion as well as presentation of techniques and methods for structural repair and prevention of corrosion by use of waterproof membranes. Even though the techniques may not be applicable to bridge decks, there is one report[12] describing cathodic protection used experimentally to control corrosion of reinforcing steel in beams of a bridge superstructure. However, use of cathodic protection to inhibit ongoing corrosion of concrete embedded steel has been well established for concrete pipelines[14-17]. This report presents results of experimental cathodic protection installation on a deteriorated bridge deck scheduled for repair, and also describes the use of experimental monomer/polymers and epoxy injection to bond delaminated concrete.

SUMMARY AND CONCLUSIONS

Cathodic protection has had a long history of successful use in protecting concrete imbedded steel in pipelines. The results of these experimental installations demonstrates that if certain conditions are met, cathodic protection can be applied to a bridge deck. One condition necessary for successful uniform application of electrical current to imbedded steel is a conductive layer of relatively low electrical resistance that can be spread over the area to be protected. Although there are other materials that can be used as an electrically conductive overlay, coke breeze was found to provide the necessary properties. When mixed with a relatively low amount of asphalt binder, the coke breeze-asphalt mixture was stable enough to function also as a base for a regular asphaltic concrete wearing course.

Prior to the installation of the cathodic protection system, the bridge deck was surveyed for halfcell potentials, and concrete delaminations by means of the chain drag. It was found that for the one year period between 1972 and 1973 prior to this work, the undersurface concrete fractures increased from 2% to 12% of the total deck area and the percentage of corrosive potentials increased from 53% to 71% of the total measurements. The average chloride-ion content of the concrete one year prior to the installation of the cathodic protection system was 3.52 pounds per cubic yard (2.09 Kg/m^3) at the level of the reinforcing steel.

Because past experience has indicated that concrete removal and replacement at delaminations has cost up to \$16/sq.ft. (\$172/m^2) of repaired area, an experiment for bonding the concrete rather than removal was performed. A methyl methacrylate, a styrene monomer, and also an epoxy was injected into the undersurface fractures. From cores, the results indicated the epoxy injection was by far the best bonding agent. However, since this was the first test with monomer injection of this kind, the results of the use of these materials are not considered conclusive.

The effectiveness of the cathodic protection was demonstrated by arresting corrosion of steel strips that were imbedded in concrete bars containing 10% calcium chloride by weight of the cement. The bars were placed within the coke breeze-asphalt layer on the bridge deck. Corrosion losses of the steel were measurable as increases in electrical resistance.

From the test results, it appears that a current density of about 0.7 milliampere per square foot (7.5 ma/m^2) of reinforcing steel surface (upper bar mat) may control corrosion in a salt laden concrete bridge deck. Measurements being recorded on the experimental deck cathodic protection system show that the corrosion is apparently controlled on about 3311 square feet (307.6 m^2) with a driving voltage of about 1.65 and about one ampere of current for a total power consumption of about 1.65 watts. As a result, power, per se, is not considered to be a limiting factor in the cathodic protection system.

Although the optimum spacing of the impressed current anodes was not clearly determined by this experiment, it appears that their effectiveness can exceed a 12-foot (3.7 m) radius. However, it appears that the maximum polarization potential of the steel should be limited to a maximum of about -1.10 volts CSE to prevent any possible loss of bond of the steel to the concrete.

It has been well established that corrosion of steel in concrete is electrochemical in nature[18-21]. The theory of cathodic protection[22,23,24] is to apply sufficient current in a proper direction so that corroding anodes on steel are prevented from discharging current (ions) into the electrolyte or, in this case, concrete. Thus, if the anodes on the steel receive current, they are no longer current-discharging anodes but are noncorroding current-receiving cathodes.

In the corrosion cell, the tendency is for the halfcell potential of the steel to come into equilibrium[23,24]. For example, if the open circuit potential of a noncorroding cathode is, say -0.10 volt (relative to the saturated copper-copper sulfate halfcell, CSE), and the corroding anode is, say -0.50 volt CSE, and then electrically connected together, the combined or equilibrium potential of both electrodes may be -0.40 volts CSE. The cathode <u>always</u> becomes more negative as it receives current from the <u>more</u> negative anode. As a result, even though the cathode will shift to a potential of -0.40 volts, it still is a cathode and may not be corroding.

From the theory of cathodic protection, it is necessary that to be protected, the existing anodes on the steel must be caused to receive electrical current. For this, the halfcell potential of all of the steel must be made more negative than the most negative potential of the anodes. For steel pipelines, empirical criterion for cathodic protection is that the steel must be made more negative than -0.85 volts CSE[25]. Although this potential value of -0.85 volts CSE has been successfully used on concrete pipelines[16], it has also been reported[26,27] that cathodic protection should be effective for steel in calcium hydroxide solutions containing chloride at potentials of about -0.71 volts CSE. In addition, other work has shown that the most anodic halfcell potential of corroded steel in corrosion caused cracked concrete was -0.67 volts CSE[28]. Excessive voltage, however, must not be used because of possible impairment of the concrete to steel bond.

It would appear that the potential of concrete imbedded steel probably should be no less than -0.85 volts CSE (where reported past experience on concrete pipelines have been successful), and not more than -1.10 volts CSE[18,26,27] to avoid the possibility of loss of bond strength. However, the possibility for controlling the corrosion of concrete imbedded steel at a potential of -0.71 volts CSE should receive further investigation.

There are two basic means[22] for applying cathodic protection which are: (1) galvanic anodes, and (2) impressed current.

In the galvanic anode system, a sacrificial metal higher in the electromotive or galvanic series is chosen because its electrical potential is more negative than the metal to be protected. Therefore, when the two different metals are electrically connected, a current will flow causing the metal under protection to receive current or become a cathode. For a bridge deck, the galvanic system appears to have two important drawbacks, which are: (1) voltage between the metals is limited to the maximum electrical potential difference, and (2) current output of the galvanic anode will vary with moisture content or electrical resistance of the electrolyte.

For bridge decks, the impressed current system has a number of distinct advantages, which are: (1) voltage output of the anodes can be varied from less than one volt to over 100 volts; (2) current output can be automatically controlled irrespective of moisture content or electrical resistance of the electrolyte; (3) halfcell potential of the steel can be automatically maintained independently of the electrical resistance of the environment.

Although various methods for applying cathodic protection to other types of structures are well known, a different system for applying cathodic protection would be required for a bridge deck. From this, it is apparent that the basic electrical circuit of steel in the deck concrete and a theory for applying cathodic protection must be developed and evaluated.

Figure 1, "Schematic of Anode in Concrete", shows some assumed electrical values for the circuit. With the anode in the concrete, it is obvious that an adjacent reinforcing steel bar theoretically can be cathodically protected. However, as indicated by the lower part of the schematic, bars beyond the most immediate one (Rebar #2) are actually in a series parallel circuit with an essentially zero resistance between bars and power source. Theoretically, in order to equally cathodically protect all the reinforcing steel, anodes would have to be placed in concrete at the location of every second bar, both longitudinally and transversely.

It is obvious that to get an effective current to Rebar #2, the anode must be removed from the concrete and placed in an electrically conductive overlay on the concrete surface to provide essentially equal resistance from all bars to the power source as shown in Figure 2.

One material that can be used as a conductive overlay is carbon in the form of coke which has had a long record of use as an anode backfill material[29]. In a dry state, coke has been reported to have a specific electrical resistance of 52 ohm cm[29] which is about twice the electrical resistance of sea water[23]. Coke is a highly conductive material as compared to the about 10,000 ohm cm resistance of water saturated concrete[30], and when wet, coke has about one-half the specific electrical resistance of sea water.

The feasibility of using a highly conductive overlay is shown by Figure 2, "Schematic of Anode in Coke". For purposes of illustration, it is assumed that the electrical resistance of the coke for the distance between the reinforcing steel in one ohm, while the electrical resistance of the concrete between the interface of the coke and concrete, to the surface of the steel is 100 ohms. From these assumptions and laws of electrical current flow, it is obvious that horizontal travel of electricity through coke would only be reduced by the ratio of one ohm resistance in the coke to the 100 ohms of concrete resistance to the reinforcing steel as the current spread out through the deck. Therefore, this general method of theory was chosen as the most promising method of applying cathodic protection to a deck.

Bridge Construction

The bridge selected for the experimental cathodic protection scheme was built in 1964 and is located at Sly Park, California, on Highway US-50, at an elevation of 4000 feet (1220 m). The average annual precipitation is 42 inches (107 cm) which includes about 18 inches (46 cm) of snowfall. The annual air temperature range is from 15° to 105°F (-9.4°C to 40.6°C).

The bridge is a continuous three span "T-beam" that is 48 feet (14.6 m) wide and 110 feet (33.5 m) long, and carries two lanes of westbound traffic.

The specifications for the concrete in the bridge deck called for 7 sacks of Type II low alkali cement per cubic yard (9.2 sacks/m^3), 4 to 4-1/2 percent entrained air. Mixing water, including that in the aggregate, was not to exceed 45 lbs./sk. (20.4 Kg/sk.) of cement, and the concrete curing was specified to have 7 days of curing by water, and a pigmented curing compound was to be applied following the wet cure.

In reviewing the construction records, only one of the many concrete cylinders could be positively identified as being from the deck concrete. The identification ticket with the sample indicated that the concrete contained 7 sacks of cement per cubic yard (9.2 sacks/m^3), (ASTM Type II modified, low alkali), had a 4-1/2 inch (11.4 cm) slump and the mixing water content was 44 lbs./sack of cement (20 Kg/sack). The 28-day compressive strength of this cylinder was 3730 psi (262 Kg/cm^2). The other samples from this bridge showed entrained air contents of 4.4% and 28-day compressive strengths ranging from 3860 to 4460 psi (271 to 313 Kg/cm^2).

The specified concrete cover over the reinforcing steel was 1-1/2-inch (3.8 cm).

Bridge Condition

Because of corrosion caused concrete spalling of the bridge deck, it had been scheduled for initial repairs and overlay during 1973 construction season. All evidence of deterioration on this bridge is the result of reinforcing steel corrosion. There is no visual evidence of distress as a result of reactive aggregate or freeze-thaw damage.

In April of 1972, this bridge was surveyed for concrete delamination, electrical potentials, depth of cover over the steel, and chloride content in preparation for the repair contract. The technique for surveying the bridge deck has been previously reported[12]. In addition, as part of the cathodic protection installation, the deck was again surveyed for concrete delamination and electrical potentials in June 1973.

Results of chloride analysis from cores is shown on Table 1 and indicates the high level of chloride-ion at the level of the steel.

Table 1

Chloride-ion in Concrete (1972)

Depth, Inches	Lbs./Cu. Yd.
0-1 (0-2.5 cm)	7.24 (4.3 Kg/m^3)
1-2 (2.5-5.1 cm)	3.52 (2.1 Kg/m^3)
2-3 (5.1-7.6 cm)	0.96 (0.6 Kg/m^3)
3-4 (7.6-10.2 cm)	0.44 (0.3 Kg/m^3)

From a total of 426 measurements with a Pachometer, the average depth of concrete cover over the reinforcing steel was 1.68-inch (4.3 cm); the standard deviation was 0.22-inch; (0.56 cm); the range was between 1.10-inch and 2.70-inch (2.79 and 6.86 cm), which indicates reasonable compliance with specifications.

Comparison of results of 1972 and 1973 electrical potential and concrete delamination survey are shown on Table 2 and indicate change in physical and electrical conditions of the bridge in one year (14 months) of service. In Table 2, the percent concrete delamination is the percentage of the total deck surface that is spalled. The percent of corrosion potential is that percentage of all measured potentials that are corrosive.

Table 2

Condition Change in Bridge

Year	% Concrete Delamination	% Corrosive Potentials*
1972	2	53
1973	12	71

*Potentials more negative than -0.35 CSE

Deck Preparation

Figures 3 and 4 show the equipotential contours for the bridge deck survey made in June 1973. Also shown are the locations of the undersurface fractures. As indicated by the extent of the fractures, it was obvious that some deck repairs had to be made prior to the application of cathodic protection. Otherwise, there was a possibility that the existing concrete spalls eventually may be loosened by traffic and thus cause structural failure of the cathodic protection overlay.

In an attempt to keep costs as low as possible, it was decided not to repair the deterioration by the process of concrete removal and replacement. Previous repairs of this kind had cost up to $16 per sq.ft. of repaired area. Instead, it was reasoned that if the concrete could be bonded together by injection of a suitable "glue", then structural loosening by traffic would be minimized. Also, if the cathodic protection system were successful, then continued corrosion-caused spalling would be stopped. Two materials were selected to use to bond the loose concrete to the underlying deck: (1) a monomer being used recently in experimental concrete impregnation studies, and (2) an epoxy resin[32]. The locations where each material was used is shown on Figures 3 and 4. At each spall, at least one 1/2-inch (1.3 cm) diameter hole was drilled into a central area. The debris from the hole was then removed by the use of an industrial type of vacuum cleaner. All injections of monomer and epoxy resin were made via these holes as shown on Figure 5.

By use of a grease gun, methyl methacrylate and styrene type of monomers were injected into the spalls. Later, 4-inch (10.2 cm) diameter cores were obtained in order to see if the concrete was truly bonded. Except for one core sample from the styrene injected area, none of the monomer injected concrete spalls were bonded. It was surmised that the methyl methacrylate was too thin and was absorbed by the concrete instead of filling the crack void. From visual observations, the styrene type monomer appeared to have great curing shrinkage which may have adversely affected bonding. However, it must be pointe out that the experimental monomer injection was performed with hand equipment. Better equipment and the selection of other monomers could have produced different results.

As shown on Figures 3 and 4, the epoxy injection, when using a maximum pumping pressure of 160 psi, was both successful and unsuccessful. The successful cases, where the cores showed the concrete was well bonded together, were found where the concrete emitted a hollow sound when the surface was struck with a hammer. The unsuccessful locations were where the chain drag indicated a hollow sound but the hammer did not. In these latter locations, the epoxy could not be injected into the spalls at the pressures normally used. Previous but unreported work (as evidenced by concrete cores) by the author has shown that the chain drag will indicate delaminated concrete in locations where the hammer method will not.

Prior to and after the injection of the monomers and the epoxy, halfcell potentials were made at the specific locations of the concrete spalls. It was found that the apparent maximum reduction in the halfcell potential of the steel after injection was in the order of 0.05 volts. Therefore, it was concluded that the injection of bonding materials would not significantly affect the penetration of cathodic protection currents to the surface of the reinforcing steel. It is surmised that for the tested areas of this bridge, the concrete within the undersurface fractures still has numerous points of contact. Therefore, filling of the void with dielectric epoxy or monomer does not create a continuous electrical shield between the reinforcing steel and the surface of the concrete. The cathodic protection currents to the steel should be effective in these areas of repair.

Electrical Continuity

The use of cathodic protection depends upon the electrical continuity of the structure being protected. If there are portions of the structure under cathodic protection that are not electrically connected to the system, ~~then~~ they can be caused to corrode by stray currents at an accelerated rate[22,29]. Therefore, care must be exercised in determining if the reinforcing steel in a bridge deck is electrically continuous.

Even with a detailed amount of testing, there is always the chance that one reinforcing bar out of the hundreds in a bridge deck may not be electrically continuous. In that case, damage will occur. If stray current damage occurs to one or two bars, the resultant concrete spalling and corrosion of the steel is expected to be no different than the condition that exists before cathodic protection is applied. However, when such a condition arises, repair can be made and the "loose" piece of steel welded to adjacent reinforcing steel. It then becomes a part of the protected grid. As a result, the corrosion can be stopped, which is not the case when using conventional methods for repairing the damage.

In practice, it has been required that at least at every third crossing of the reinforcing steel, a tie wire be used to mechanically interconnect the steel. Therefore, there is a strong likelihood that all reinforcing steel will be interconnected simply by normal construction procedures.

In a previous report[28], it was shown that if the halfcell were left in the same location on a deck surface, the measured halfcell potentials would be different if an electrical contact were made to various electrically disconnected pieces of steel imbedded in the concrete. Conversely, if the steel were interconnected, the halfcell potential relative to a stationary halfcell would be the same, irrespective of the location of the connection to imbedded steel. This assumes that the electrical resistance of the steel is minor as compared to the electrical resistance of the concrete.

On the Sly Park Bridge, at four equidistant locations along the curb line and also on the concrete section of the railing, the electrical measurements showed that all reinforcing steel was interconnected. However, the bolted-on aluminum guardrail was not electrically connected to the reinforcing steel.

For the "ground" of the cathodic protection system, at all four deck locations at which the steel was used for continuity testing, No. 8 direct burial stranded copper wires were welded to the bars and brought out to the control panel.

Control Cabinet

As shown in Figure 7, a standard traffic controller cabinet was modified to house the electrical circuitry and the standard automotive type 6 and 12-volt battery power sources.

Also installed on a panel inside of the cabinet are 36 each of 3 ohm, 5 watt wire wound resistors. The purpose of these resistors is to control the amount of direct current to each of the anodes. This current control capability is necessary because of the expected variations in the electrical resistance of the portland cement concrete and coke breeze asphalt concrete.

Included within the control panel are selector switches that allow the measurement of current flow by means of an

0.01 ohm shunt in series with each anode connection.

An ammeter is also installed on the panel to measure gross current flow. There are provisions for external equipment, such as a timer, that will automatically turn the current on and off so that polarization measurements can be obtained. The control panel without modification is to be used with an automatic potential control cathodic protection rectifier.

Coke Breeze-Asphalt Concrete

Insofar as coke breeze has been used as a backfill material for impressed current cathodic protection anodes, its feasibility as an asphalt concrete aggregate was evaluated. As received, the coke breeze No. 90 was graded and found to meet January 1973 California State Division of Highways Stnadard Specifications for aggregate grading of 3/8-inch maximum aggregate for asphalt concrete.

Some of the physical properties determined were:

Specific Gravity of Aggregate was 1.64 - the S.G. of the mix with 15% of 85-100 penetration asphalt was 1.25 (Test Method No. Calif. 38).

The "K" value of the coarse coke breeze was 3.0 and the "K" of the fine aggregate was 1.7 (Test Method No. Calif. 303).

The surface area of the mix was 37.4 sq.ft./lb. (7.66 m^2/Kg), (Test Method No. Calif. 303).

The stabilometer value for a mixture of coke breeze and 15% of 85-100 penetration asphalt was approximately 28, (Test Method No. Calif. 304).

Based on preliminary work, it was determined that for optimum electrical properties, coke breeze should be 3 inches (7.6 cm) thick. However, with the lower asphalt content mixtures tested, it was obvious that they would not be sufficiently cohesive to be exposed directly to wheel loads. Therefore, it was decided to overlay the coke-AC layer with about 2 inches of a dense graded 3/8-inch (0.95 cm) maximum natural aggregate asphalt concrete for a total overlay thickness of 5 inches (12.7 cm).

In order to determine the durability of composite pavement, a 50-ft. long by 12-ft. wide (15.2 x 3.66 m) test section was placed upon a new but unused portland cement concrete pavement. After mixing at a plant, the coke breeze-asphalt concrete was spread by using a Layden box spreader and initial rolling was done with a 4-ton (3.6 M.T.) roller. The final rolling was completed with a 10-ton (9.1 M.T.) roller. The coke breeze was mixed with 15% of 85-100 penetration asphalt while the 3/8-inch (0.95 cm) maximum natural aggregate wearing course was mixed with 5.4% of the same asphalt.

At one end, a 12-ft. (3.66 m) length of 5-inch (12.7 cm) thick all natural aggregate asphalt concrete was used as a control section. In the test section, the coke breeze layer was covered with Petromat. However, after the natural aggregate AC was placed, it was observed that the Petromat tended to wrinkle and its further use was questioned at that time. It was not used on the bridge overlay. A Dynaflect was used to measure deflections and cross-sections were taken at various stations.

To quickly test the load carrying capacity of the composite pavement, a 10-wheel truck weighing about 44,000 lbs. (20,000 Kg) complying with the legal load limit of 18,000 lbs. (8163 Kg) per axle was used to apply loads to the test section. The results were that at the end of 3802 passes of the truck, no distress was observed or measured.

On the basis of this test series, it was decided that the composite asphalt concrete pavement would be reasonably durable when used on a bridge deck.

Installation of Anodes and
Overlay (on the Bridge Deck)

The iron-alloy anodes were disc shaped, 10 inches (2.54 cm) in diameter, and 1-1/4-inches (3.2 cm) thick, and had an average weight of approximately 29 pounds (13.2 Kg). Based on test data[31] for similar anodes, they would have a consumption rate of about 1/4 pound per ampere year of current flow. In other words, if one ampere was caused to be continuously discharged by the anode, it would be entirely consumed by corrosion in about 116 years.

Initially three rows of anodes were laid out on the bridge deck 12-feet (3.66 m) center to center. The anodes in effect were placed on 12-foot (3.66 m) centers directly beneath the three traffic stripes that delineate the two lanes across the bridge. After marking out locations of the anodes on the pavement, a fast setting epoxy adhesive (California Standard Specification 721-80-42) was placed on the concrete surface and the anode was then placed on the epoxy. The use of the epoxy was considered two-fold: (1) to hold the anodes in place during the paving operation, and (2) to prevent current discharge from the bottom surface of the anode. It is considered that limiting the current discharge from the bottom of the anode would inhibit the lifting of the anode which could cause pavement distress due to the formation of a layer of rust between the anode and the concrete pavement. Also, the epoxy layer would reduce the current discharge directly beneath the anode which could cause a high current density flow to the reinforcing steel directly under it, and thus result in a "hot spot".

At the conclusion of the paving operation, it was found that one out of 36 anode connections was damaged. It is suspected that the damage was caused by the roller passing close to the point where the lead wire leaves the anode, thereby pulling it loose.

Prior to paving of the bridge deck, an SS-1 asphalt emulsion tack coat was applied at a rate of 0.05 gal./sq.yd. (0.23 l/m^2). Previous electrical testing on the pavement test section showed that use of the tack coat at this rate of coverage would not adversely affect the electrical performance of the cathodic protection system.

The coke breeze was initially dried at the batch plant to a temperature of about 230°F (110°C) to which the 85-100 penetration grade asphalt at 310°F (155°C) was added. Final temperature of 21 tons (19 M.T.) of coke breeze-asphalt concrete at the batch plant ranged between 240°F (116°C) and 270°F (132°C). The haul distance from the batch plant to the bridge was approximately 55 miles. A Blaw-Knox rubber-tired paving machine was used to lay all asphalt in about 10-foot (3 m) widths. An area approximately 1500 sq.ft. (139.5 m^2) was paved with an all natural aggregate asphaltic concrete. The five anodes in this area cannot operate as intended and are, therefore, not included in the protection system. As will be discussed later, only seven of the remaining anodes were needed to provide the desired protection.

The coke breeze asphalt concrete layer was initially consolidated with a 4-ton (3.6 M.T.) roller with the final passes made with a 12-ton (10.9 M.T.) roller. Initially, there was some "shoving" of this mixture because of its lack of cohesion. Further studies are being made to improve the cohesion of the coke breeze asphalt concrete by using a heavier grade of asphalt and/or a higher asphalt content.

The natural aggregate asphalt mix for the surface or wearing course arrived on the jobsite at a temperature of 270°F (132°C) and its placement in 1-inch lifts and rolling to final grade was performed without incident.

Thus far, (two months of service) no evidence of distress has shown up on the pavement due to traffic which includes up to maximum legal load limits of commercial and logging truck traffic. However, the pavement has not yet been subjected to inclement weather, such as rain or snow, or to chain traffic.

Figure 6 shows the anodes in place, and the paving operation in progress.

Figures 8, 9, 10, and 11 show the actual depths of the loose or uncompacted coke breeze asphalt concrete as well as the area that contains full depth (5-inch (2 cm)) natural aggregate asphalt concrete. As will be noted on these latter figures, the thickness of various areas of the uncompacted depth of coke breeze is 3-1/2, 3, and 2-1/2 inches (8.9, 7.6, and 6.4 cm). The varying depth of coke breeze asphalt concrete was used to explore the feasibility of reducing the total depth of the composite asphalt concrete.

The Sly Park bridge does not have expansion joints, therefore no consideration was given to the use of expansion dams.

Circuit Resistance

After the installation was completed, but before any current was applied, electrical measurements were made on the deck at various intervals of time. It was observed that for about one week after construction the halfcell potentials of the steel would not reasonably duplicate those values that were originally measured on the concrete surface.

It was speculated that when the hot (270°F, (132°C)) asphalt concrete was placed on the deck surface, free water was driven out of the portland cement concrete. In the dry and hot climate typical at the time of construction (air temperatures in the mid-90°F's, (32°C)) it took a little over seven days for the moisture level to increase enough to make the upper surface of the concrete electrically conductive.

By use of a commutated direct current ohm meter, the average electrical resistance was measured between the anodes and the reinforcing steel. The average values of electrical resistance for the various uncompacted thicknesses of coke breeze asphalt concrete is shown on Table 3. Compacted thickness is probably about 1/2-inch (1.3 cm) less than that shown on Table 3.

Also shown on Table 3, are the average electrical resistance values when cathodic protection was being applied at a current of 1.01 amperes and a driving voltage of 1.65 volts.

Table 3

Anode to R-Steel, Ohms

Uncompacted Depth of Coke AC	2-1/2 Inch (6.3 cm)	3 Inch (7.6 cm)	3-1/2 Inch (8.9 cm)
Comutated D.C. Resistance	1.43	1.16	1.09
After Polarization	14.7	12.1	9.3

As will be noted, there is a significant difference in electrical resistance for the different uncompacted depths of the coke breeze asphalt concrete. The effect of polarization during the flow of cathodic protection currents is also shown as an electrical resistance for the different depths of coke asphalt concrete on Table 3. It should be pointed out that the measurements were made on the compacted composite pavement and the term "uncompacted depth" applies to the depth of the asphalt concrete before compaction or consolidation.

It has been previously pointed out that during the process of cathodic protection, the polarization of the anode and cathode results in a back electromotive force (EMF)[22,29].

In the case of the Sly Park bridge, when the anodes were disconnected, the polarization voltage (or back EMF) that was measured between the anodes and reinforcing steel was an average of 1.44 volts.

The locations of the seven operating anodes outside the travelled lanes are shown on Figures 8, 9, 10, and 11. The only reason that not all of the anodes are being used is that it was found during the preliminary testing it was possible to sustain the cathodic protection system without using all of the installed anodes. The location of the anodes being used have a mechanical and economical advantage over the use of anodes that were installed in the travelled lanes. These anodes would be subject to greater traffic loading as compared to those in the shoulder and median areas of the bridge.

Distribution of Cathodic Protection Currents

It was initially planned that for equal current distribution throughout the bridge deck surface all of the originally installed anodes might be used. However, initially, four adjacent anodes that were located at the shoulder side of the west end of the bridge were turned on with a total current flow of 3.6 amperes. It was found that the cathodic protection currents could polarize the reinforcing steel to a protective potential for a longitudinal distance of 65 feet (19.8 m) from the nearest anode. Also, the steel began to polarize quite rapidly so that after two hours, the output current from the four anodes was reduced to 2.0 amperes. Three days later, the current flow to the four anodes was further reduced to 1.6 amperes. Seven days later, the four anodes at the one end of the bridge were deactivated and the seven anodes (as shown on Figures 8, 9, 10, and 11) were activated with a total current output of 1.08 amperes.

Table 4 shows the performance of the seven anodes after 19 days of operation. The anodes that are numbered 1-1 through 1-9 are near the shoulder area, with the smallest numbered anode (1-1) being at the most westerly end of the bridge. The anodes numbered 3-1 and 3-4 are nearest the centerline, or median area of the twin bridge installation.

Table 4

Operating Characteristics of Anodes

Anode	Amp	Driving Voltage	Back EMF
1-1	0.12	1.65	1.48
1-3	0.12	1.65	1.52
1-5	0.21	1.65	1.42
1-7	0.20	1.60	1.38
1-9	0.15	1.60	1.38
3-1	0.10	1.72	1.42
3-4	0.15	1.82	1.48

Figures 8 and 9 show the voltage gradients relative to the CSE when the cathodic protection currents are "on". Even though the current is "on", the measurements of the halfcell potential of the reinforcing steel beneath the 5-inch (12.7 cm) thick nonconductive natural aggregate asphalt concrete are unaffected, and near the same values as originally measured and shown on Figures 3 and 4. This shows that the steel in this area is not affected by the other parts of the system and the basic theory of deck protection is confirmed (ie, no current will flow through the nonconductive AC layer).

Figures 10 and 11 show the current "off" condition, or distribution of the polarized halfcell potentials of the steel.

From these latter figures, it will be noted that maximum range of the difference of polarized potentials of the steel is 0.35 volts. Also, as indicated by the potentials being more negative than -0.85 volts, the cathodic protection currents should be effectively controlling the corrosion of the steel.

Even though the activated anodes shown on Figures 8, 9, 10, and 11 are at a 24-foot &7.3 m) C/C spacing, the inactive anodes could be energized resulting in a more even distribution of potentials. However, as previously pointed out, it is desirable to have the cathodic protection system operate with anodes not placed in the travelled lanes of the pavement. The inactive anodes will be placed under cathodic protection so that when or if the operating ones are consumed or become inoperative, the inactive ones will be available for use to eliminate the necessity for installing new anodes.

The "storage" of inplace inactive anodes by cathodic protection that are installed at the same time as the active anodes may be of considerable value on structures of high vehicular density where maintenance operations are of critical concern.

To determine if the cathodic protection currents were affecting the bottom mat of reinforcing steel, measurements were made and it was found that the halfcell potential of this steel changed only a few millivolts when the cathodic protection current is turned on and off. The bottom mat is not significantly affected by the cathodic protection currents so any corrosion of this steel will not be controlled by the system.

Because the two mats of steel are interconnected by the "crank" or truss bars, a calculation of the cathodic protection current density to the surface of the steel can only be an estimate. Therefore, for this particular structure, the existing current density used to obtain cathodic protection is estimated to be about 0.7 ma/sq.ft. (7.5 ma/m^2) for the top mat of steel.

As an indication of the distribution of the halfcell potentials of the reinforcing steel, Figure 12 shows the original current "on" and the polarized or current "off" potentials.

From Figure 12, it is seen that 98% of all of the polarized potentials are greater than -0.85 volts; therefore about 2% of the area of the steel within the conductive asphalt concrete may not have adequate cathodic protection. The potentials at those locations of less than -0.85 volts CSE can be easily changed increasing the current output of the anodes.

Although the conditions reported were observed during battery operation, a rectifier has been installed that will automatically control the cathodic protection current according to the halfcell potential of the steel. As a result, a permanent halfcell is being placed on the deck that will provide the means for the rectifier to "sense" the halfcell potential of the steel and make automatic adjustments of the current. Automatic operation will supply the proper level of cathodic protection regardless of other varying conditions.

Cathodic Protection - Effectiveness

Literature references are cited wherein effectiveness of a cathodic protection system can be related to the polarized halfcell potential of the steel. However, since this might be the first demonstration of cathodic protection on a bridge deck and involves some unique features as compared to, say pipelines or tanks, effectiveness of the system should be demonstrated preferably by a short-time test. A test of sorts was devised to measure the effect of the system on corrosion of steel strips imbedded in 3x3x12-inch concrete blocks containing 10% calcium chloride by weight of cement. By external means, the steel strips are measured to determine their electrical resistance. Any corrosion of the steel strips will result in a change in their cross-section and thus there will be an associated change in electrical resistance of the steel. This technique has been widely reported[33] and used.

The concrete blocks and imbedded steel strips described above were placed in the conductive asphalt/coke concrete as shown on Figure 13.

Referring to Figure 13, steel strip No. 1 was allowed to corrode for 6-1/2 days before being connected to the cathodic protection system. As will be noted, corrosion was essentially stopped after the application of cathodic protection current. The polarized potential of the strip was measured and found to be -1.31 volts CSE.

Steel Strip No. 2, which also was imbedded in the same kind of concrete, was placed in the electrically conductive asphalt/coke concrete and immediately connected to the cathodic protection system. As will be noted on Figure 13, essentially no corrosion occurred. After six days, the strip was disconnected from the cathodic protection system and corrosion began.

However, as shown by the performance of steel strip No. 2, the loss of cathodic protection does not result in an immediate and catastrophic corrosion rate because of the apparently long term "decay" of polarization. The halfcell potential of steel strip No. 2 was -0.67 volts CSE on the twentieth day of test.

As indicated by the corrosion measurements of the steel strips with and without cathodic protection applied, the system is feasible and does control corrosion of embedded steel.

However, the long-time durability and performance of the paving system and the anodes themselves have not yet been confirmed for this type of application.

There is still the possibility that there will be pavement failure as the result of untouched and loose concrete spalls in the deck. However, such failures would not be considered a failure of the cathodic protection system, but only an indicator of necessary deck preparation prior to the placement of the overlay.

Cost of Cathodic Protection

Although an experimental installation provides a poor criterion of costs, it is, at this time, the only available indicator. Therefore, the costs of the cathodic protection installation is to be regarded as an estimate, and could vary considerably from that shown.

Item	Estimate
Paving (Including cost of coke breeze)	$ 8867.57
Epoxy Injection (Repairs of deck)	1507.50
Anodes	1500.00
Install Anodes	75.00
Wiring (AC power)	1600.00
Rectifier	900.00
Control Panel	1500.00
	$15950.07

Based on the total square feet of deck area, the cost for the cathodic protection system was about \$3/sq.ft. (\$32/sq.m) of deck area. This fugre does not include the cost of the original bridge survey, nor testing that was performed subsequent to the installation of the cathodic protection system.

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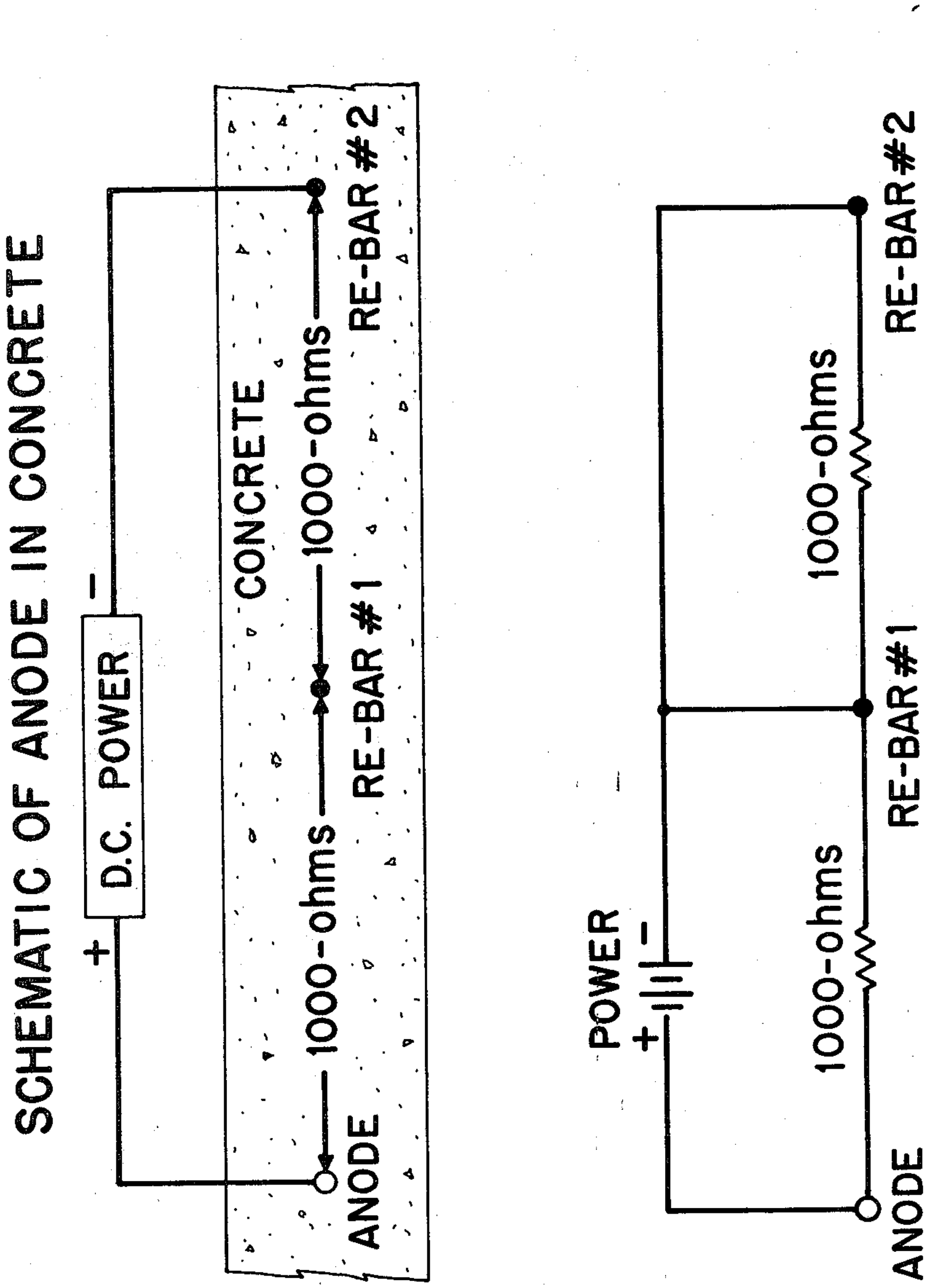
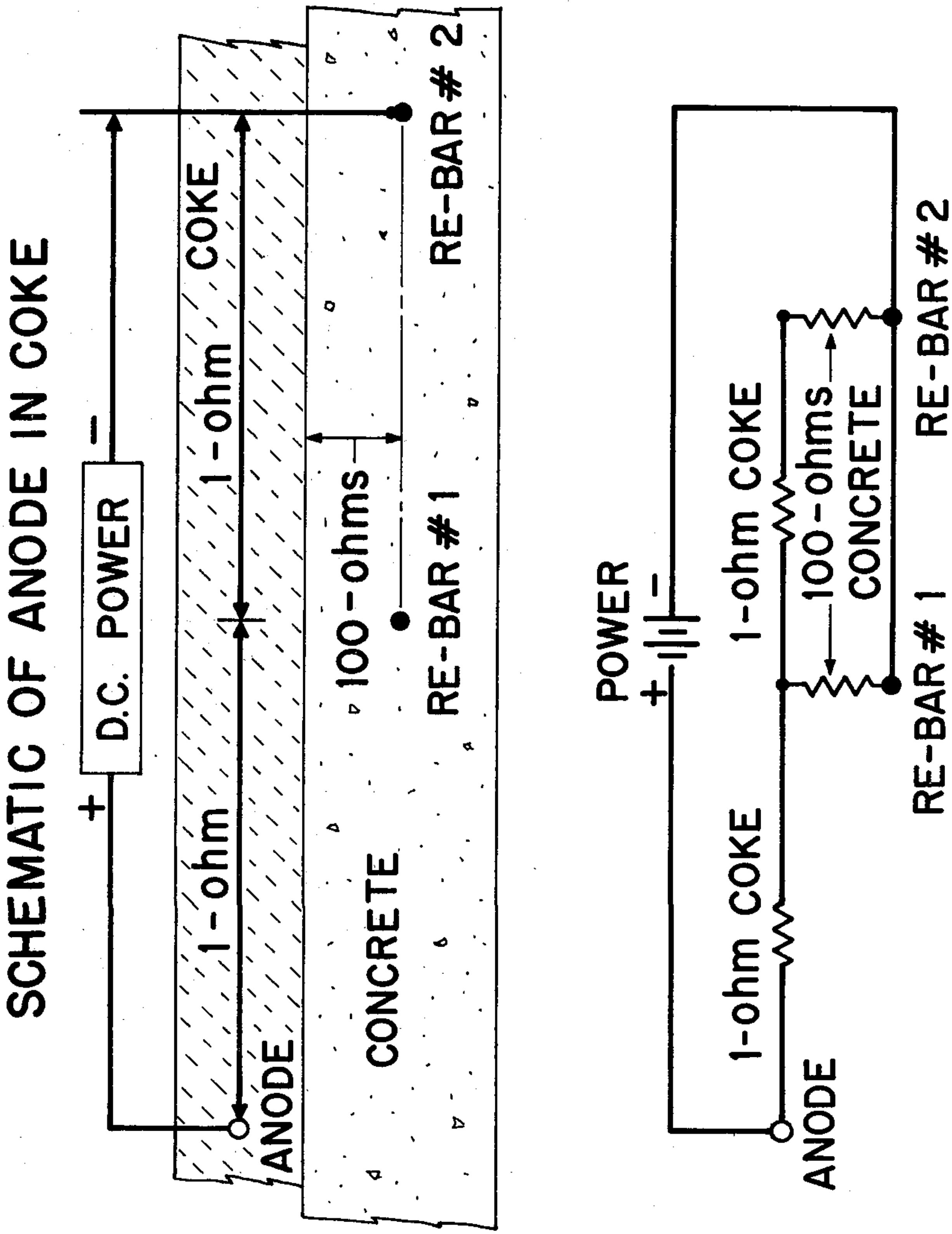
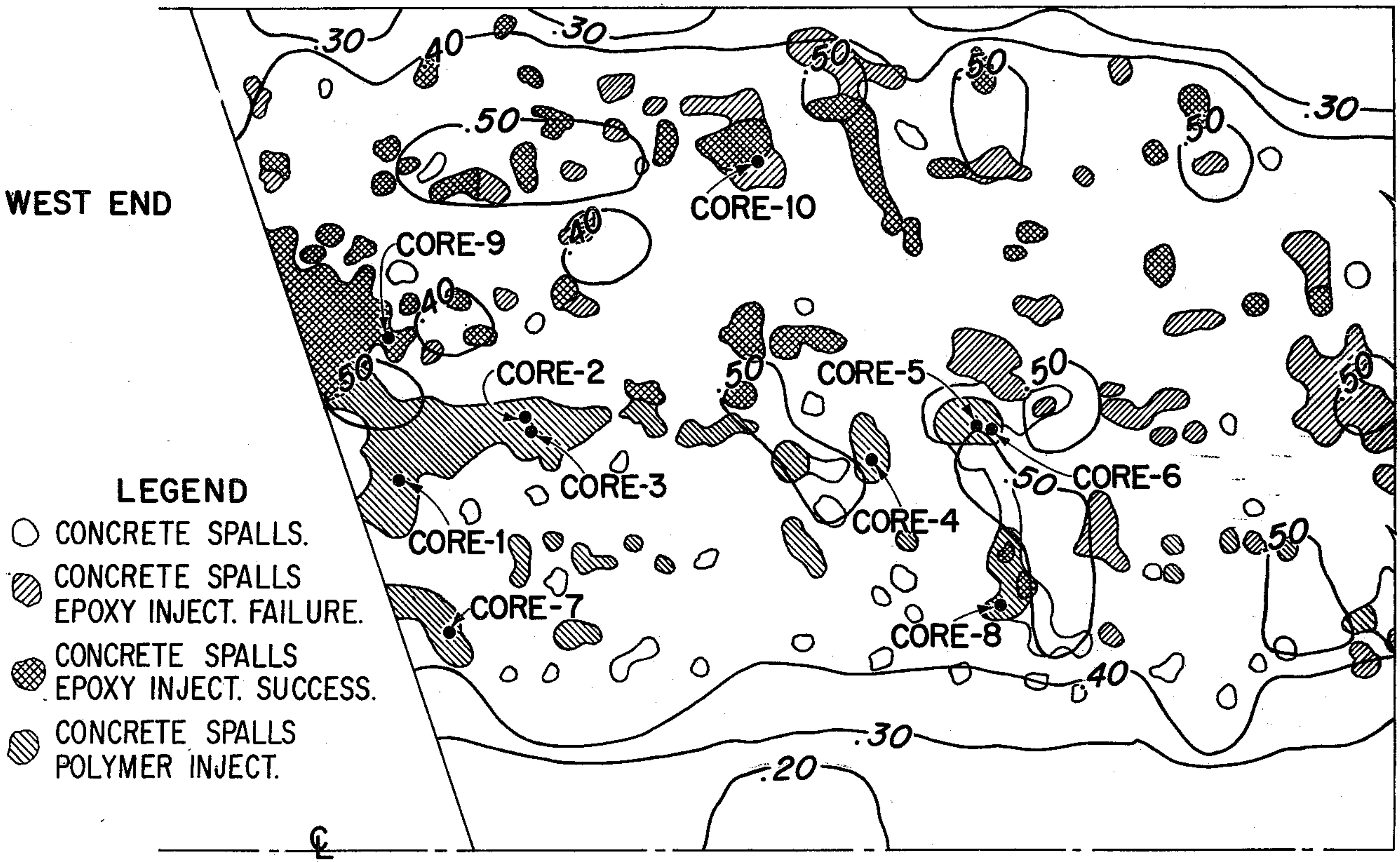

SCHEMATIC OF ANODE IN CONCRETE
D.C. POWER
+
-
CONCRETE
ANODE
1000-ohms
RE-BAR #1
1000-ohms
RE-BAR #2
POWER
+
-
1000-ohms
RE-BAR #1
1000-ohms
RE-BAR #2
ANODE

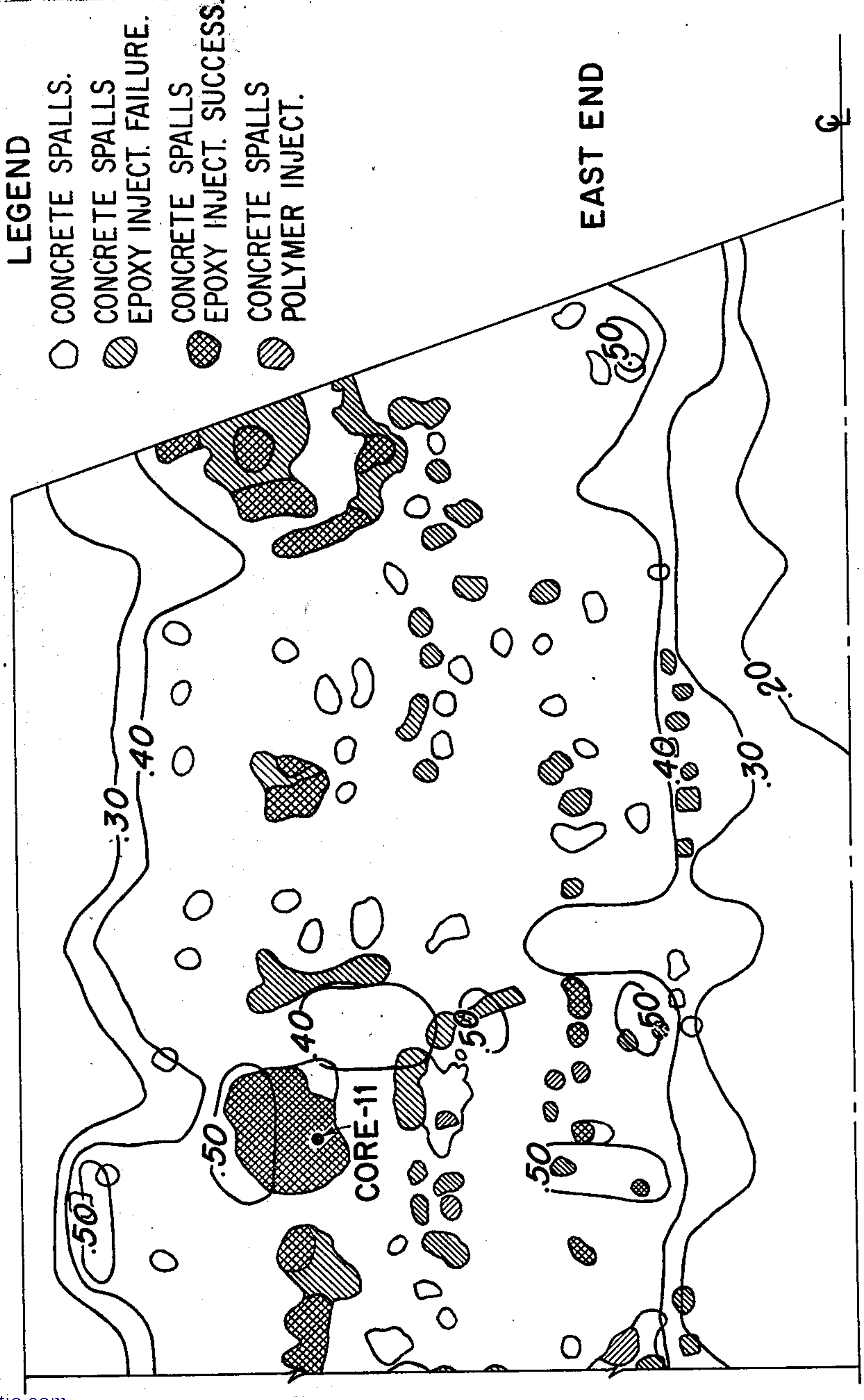
Figure 2


SCHEMATIC OF ANODE IN COKE
D.C. POWER
+
-
COKE
1-ohm
1-ohm
100-ohms
CONCRETE
ANODE
RE-BAR # 1
RE-BAR # 2
POWER
+
-
1-ohm COKE
1-ohm COKE
100-ohms
CONCRETE
RE-BAR # 1
RE-BAR # 2
ANODE

ORIGINAL HALF CELL POTENTIALS
AND CONCRETE SPALLS



ORIGINAL HALF CELL POTENTIALS AND CONCRETE SPALLS



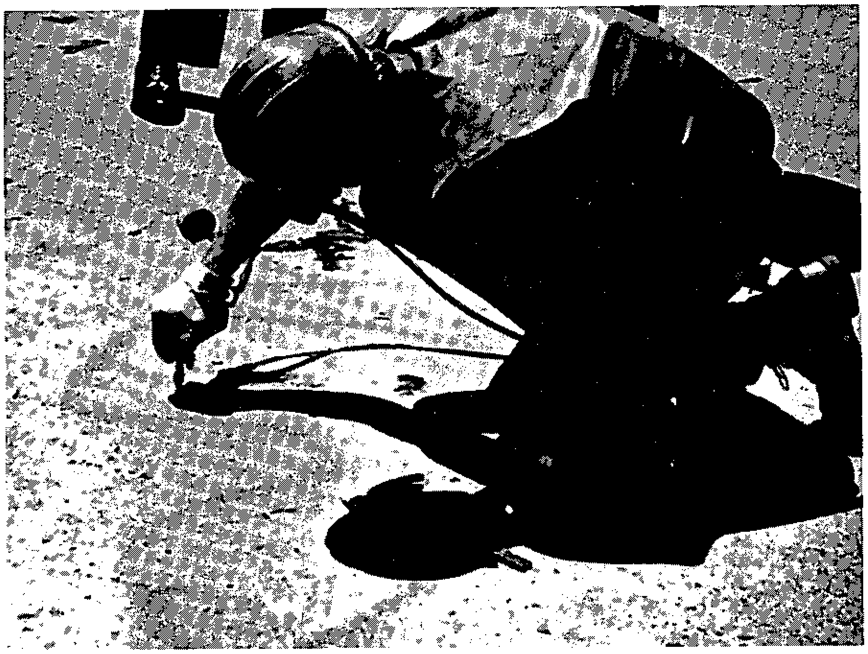


Figure 5. Injecting Epoxy into undersurface fractures.

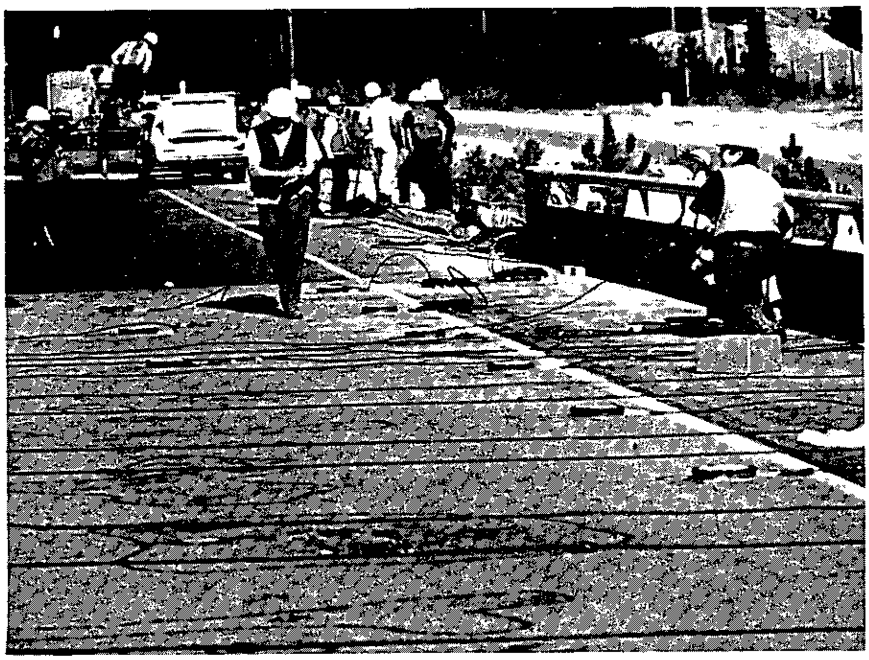


Figure 6. Anodes on concrete surface

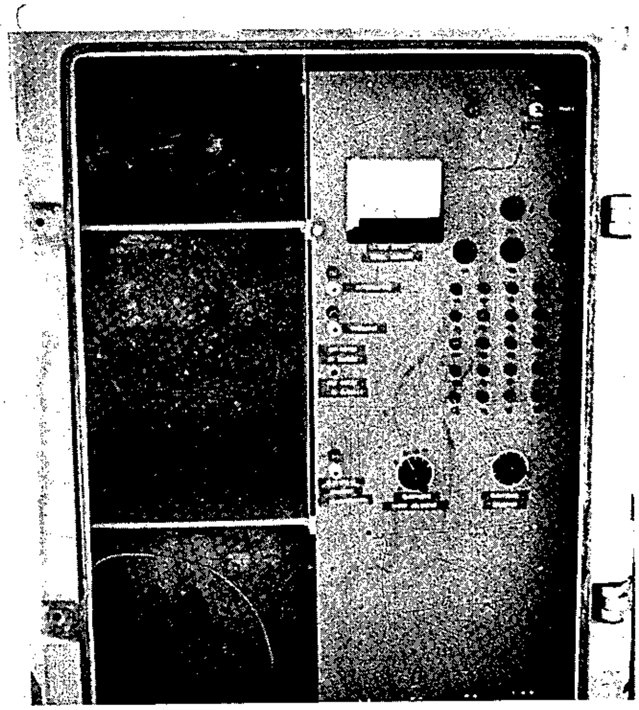


Figure 7. Panel for controlling current to anodes

Figure 8

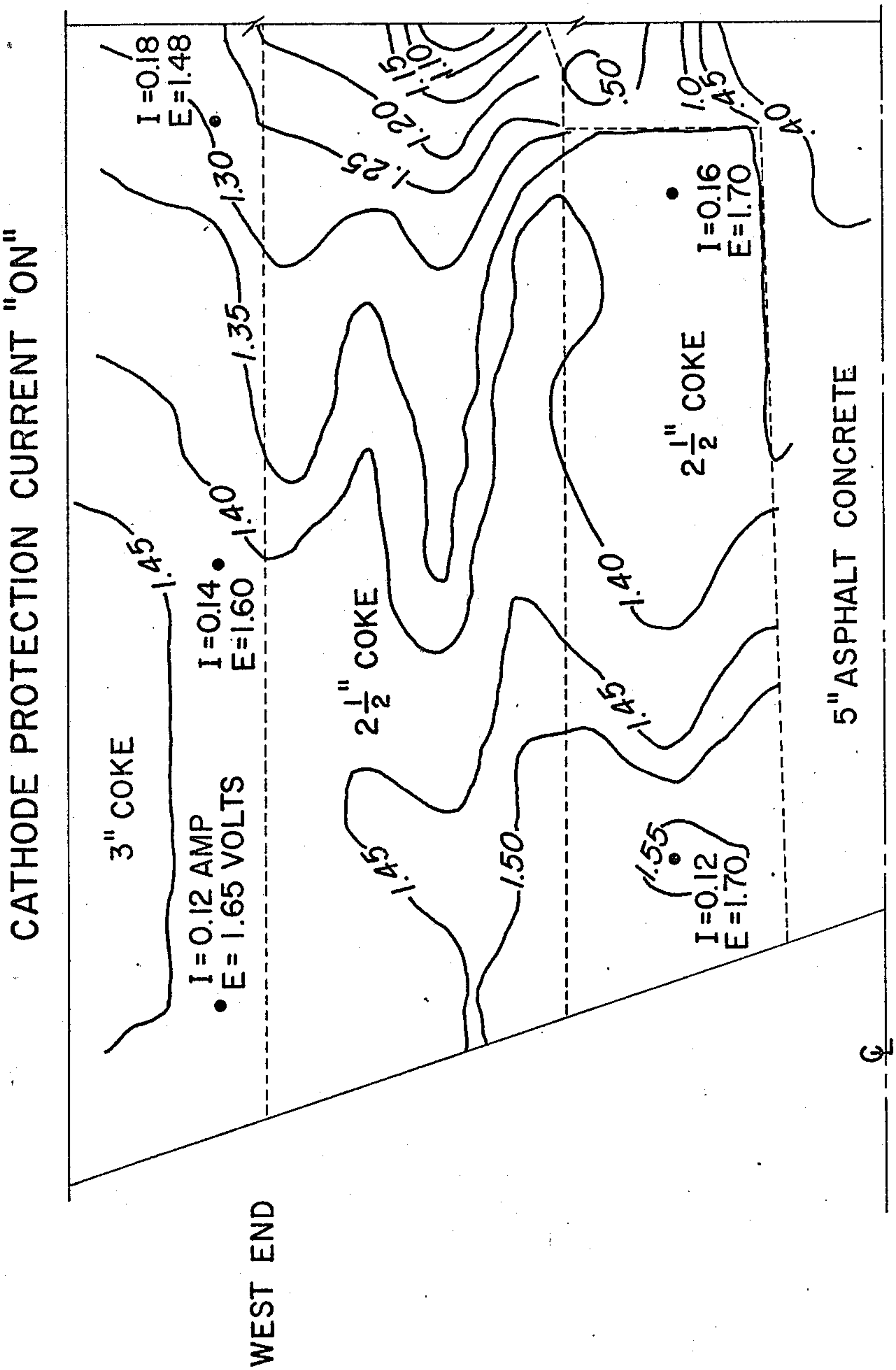

CATHODE PROTECTION CURRENT "ON"
3" COKE
I = 0.12 AMP
E = 1.65 VOLTS
I = 0.14
E = 1.60
I = 0.18
E = 1.48
2 1/2" COKE
2 1/2" COKE
I = 0.16
E = 1.70
I = 0.12
E = 1.70
5" ASPHALT CONCRETE
WEST END
1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.50
1.55
1.0
.45
.40
.50

Figure 9

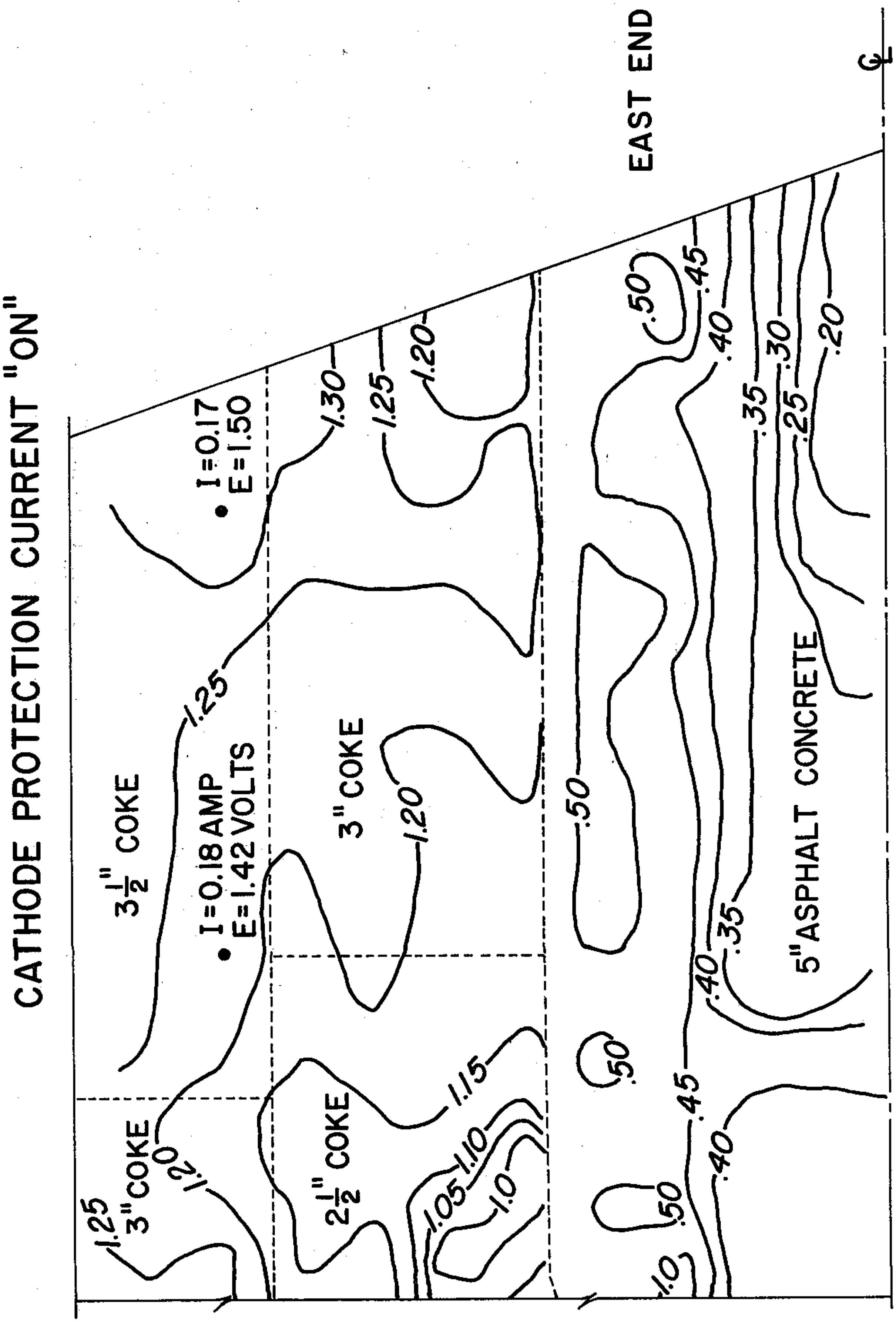

CATHODE PROTECTION CURRENT "ON"
EAST END
℄
I=0.17
E=1.50
I=0.18 AMP
E=1.42 VOLTS
3 1/2" COKE
3" COKE
3" COKE
2 1/2" COKE
5" ASPHALT CONCRETE
1.30
1.25
1.20
1.25
1.20
1.15
1.10
1.05
1.0
1.25
1.20
.50
.45
.40
.35
.30
.25
.20
.50
.50
.50
.45
.40
.40
.35
1.0

Figure 10

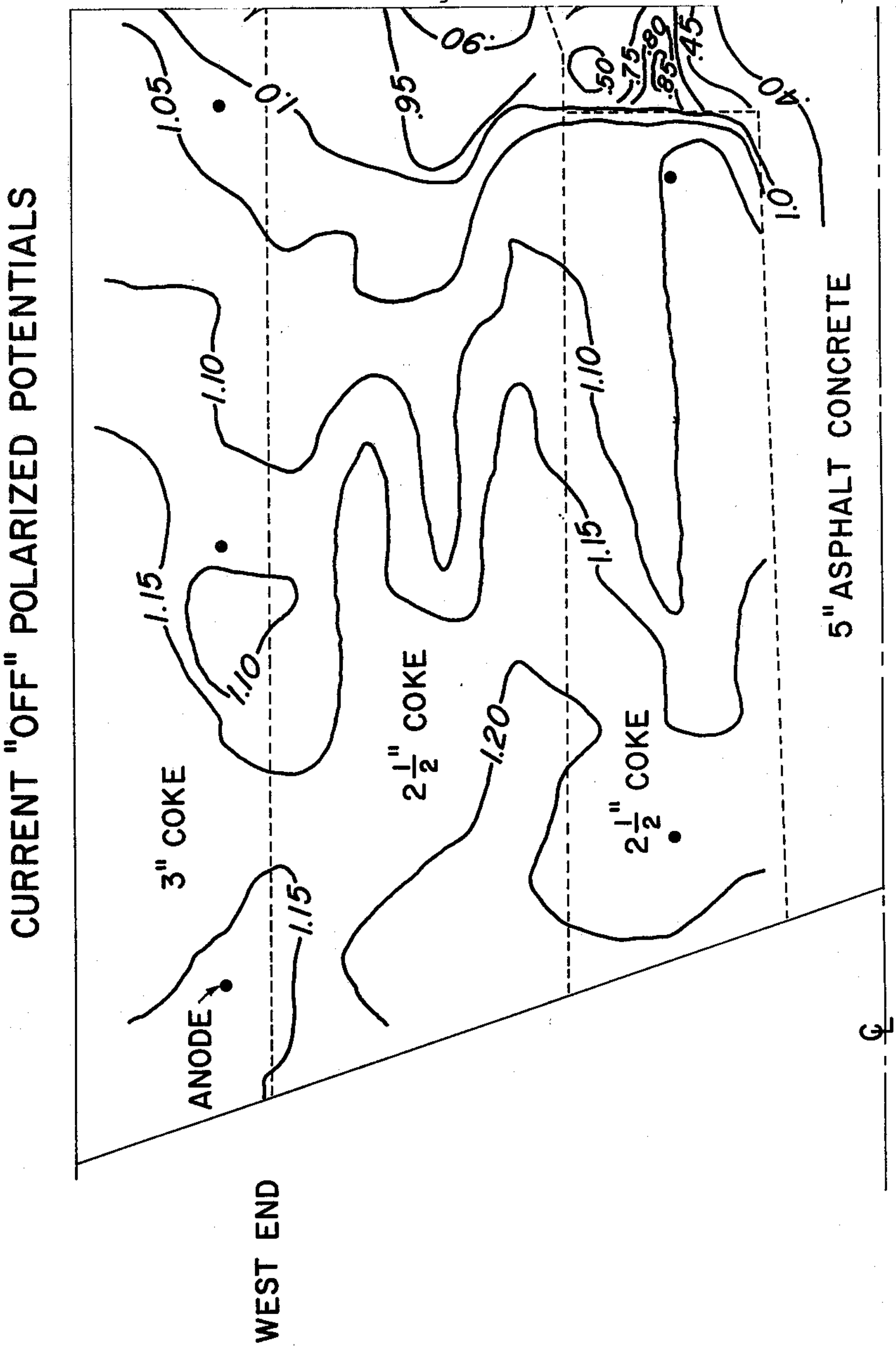
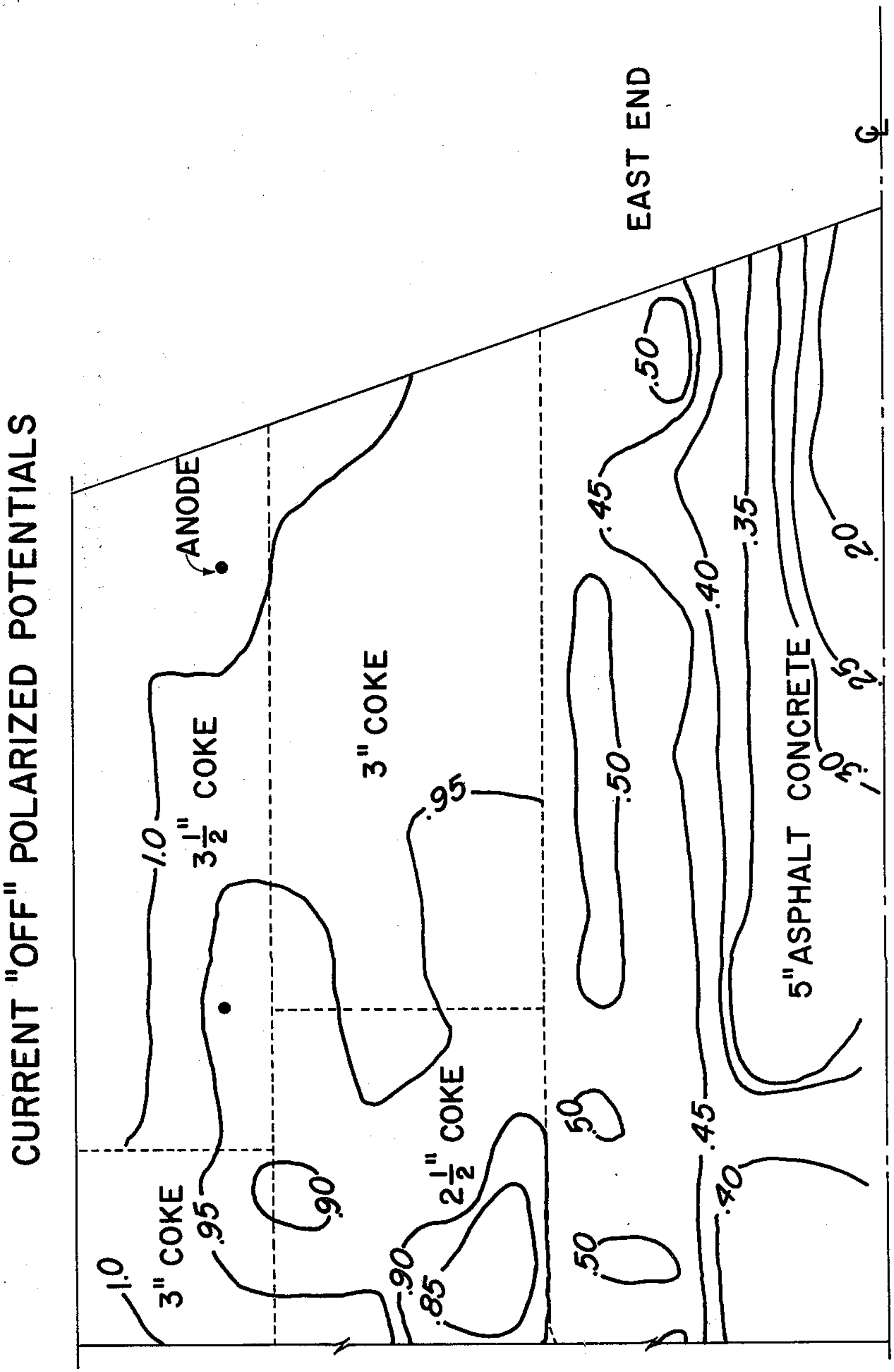

CURRENT "OFF" POLARIZED POTENTIALS
3" COKE
$2\frac{1}{2}$" COKE
$2\frac{1}{2}$" COKE
5" ASPHALT CONCRETE
ANODE
WEST END
1.05
1.0
.95
.90
.50
.75
.80
.85
.45
.40
1.0
1.10
1.10
1.15
1.15
1.10
1.20
1.15

Figure 11


CURRENT "OFF" POLARIZED POTENTIALS
EAST END
ANODE
3½" COKE
3" COKE
3" COKE
2½" COKE
5" ASPHALT CONCRETE
1.0
1.0
.95
.95
.90
.90
.85
.50
.50
.50
.50
.45
.45
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.35
.30
.25
.20

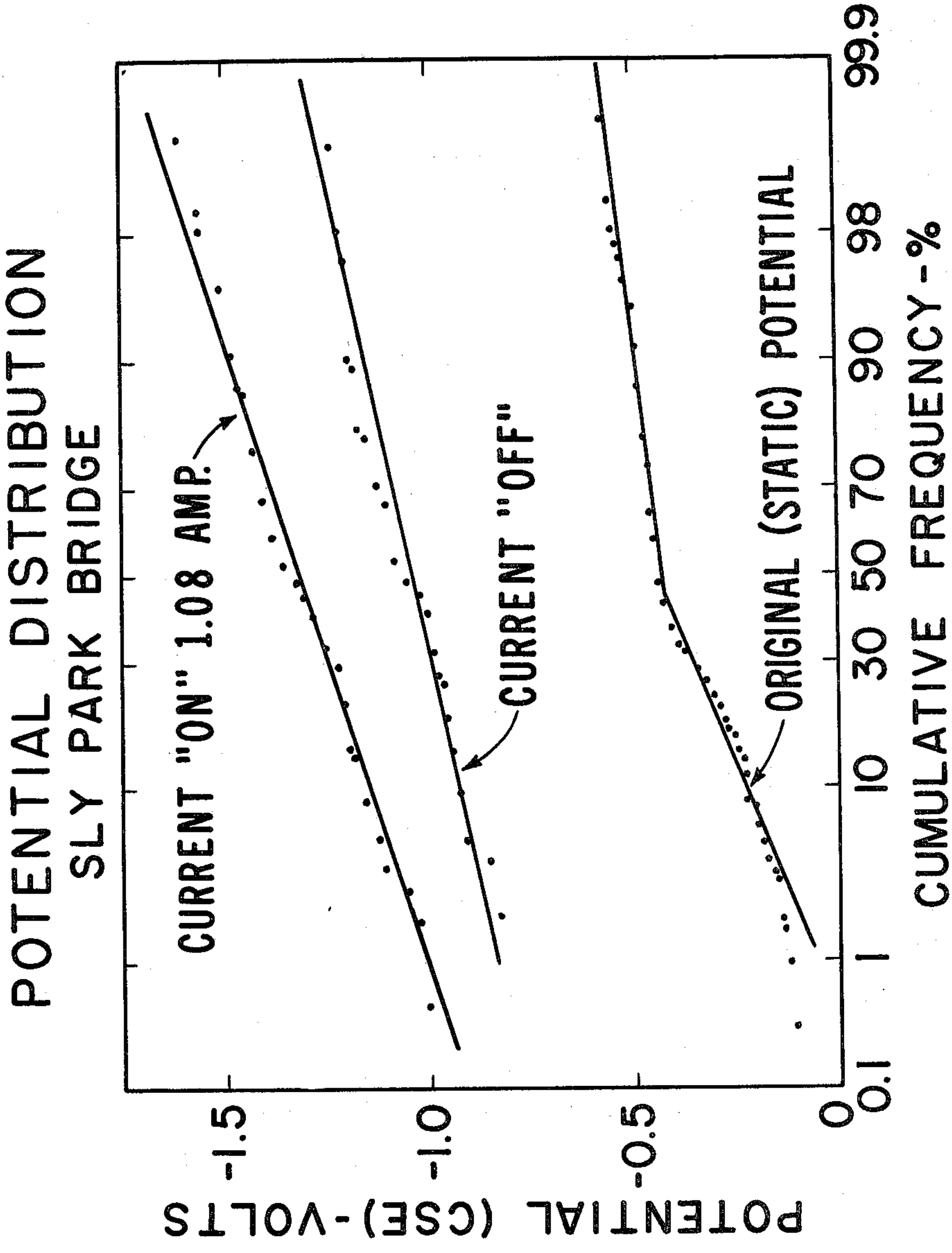
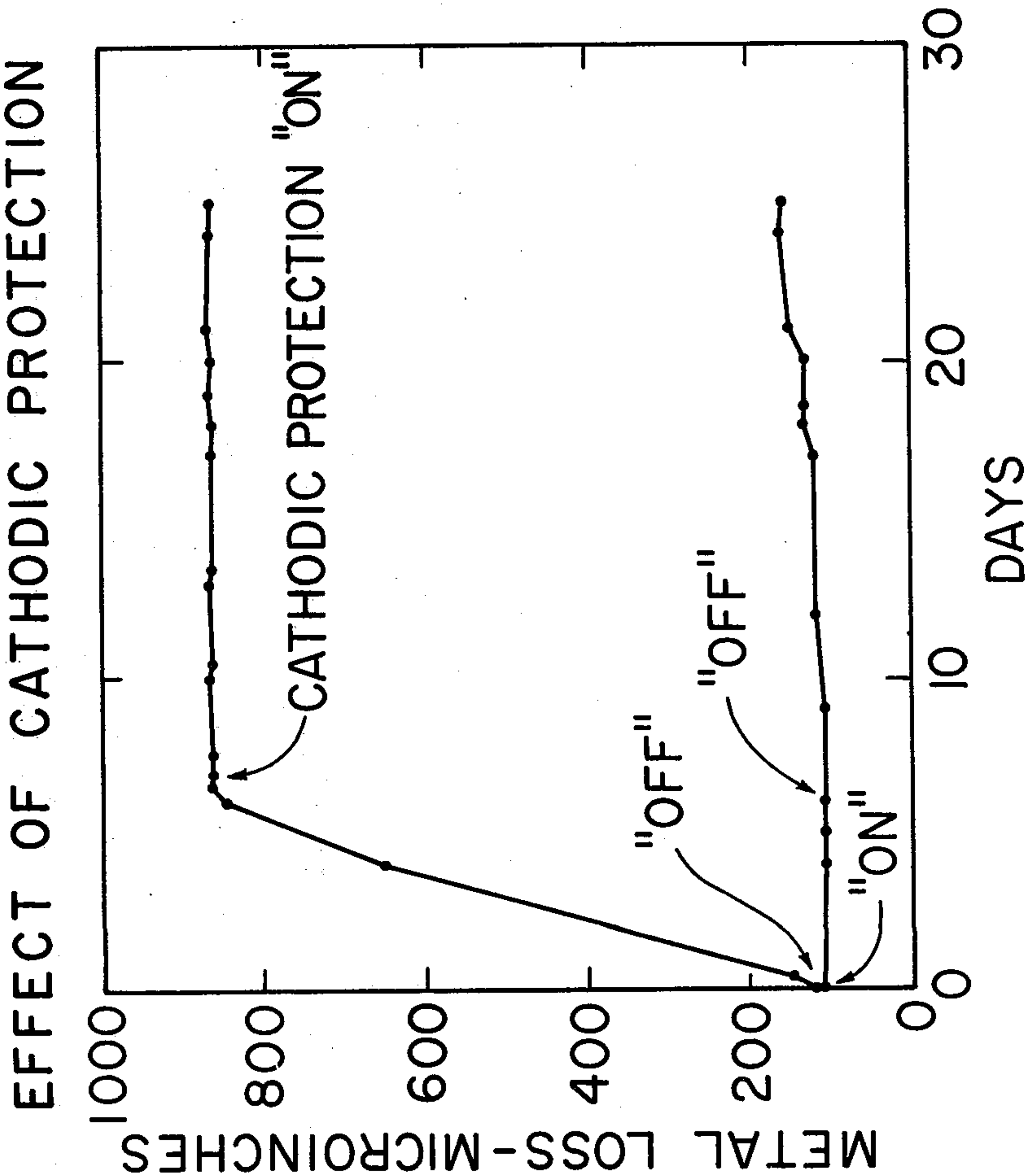

POTENTIAL DISTRIBUTION
SLY PARK BRIDGE
CURRENT "ON" 1.08 AMP.
CURRENT "OFF"
ORIGINAL (STATIC) POTENTIAL
POTENTIAL (CSE)-VOLTS
-1.5
-1.0
-0.5
0
CUMULATIVE FREQUENCY-%
0.1
1
10
30
50
70
90
98
99.9

Figure 13


EFFECT OF CATHODIC PROTECTION
CATHODIC PROTECTION "ON"
"OFF"
"OFF"
"ON"
METAL LOSS-MICROINCHES
1000
800
600
400
200
0
0
10
20
30
DAYS